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TECHNICAL REPORT No. 128

A SUMMARY OF THE RESULTS OF STUDIES OF ACOUSTIC PROPAGATION IN THE VERTICAL PLANE (U)

H. B. Sherry

April 26, 1966

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Hudson Laboratories
of
Columbia University
Dobbs Ferry, New York 10522

Alan Berman
Director

Technical Report No. 128

A SUMMARY OF THE RESULTS OF STUDIES OF ACOUSTIC PROPAGATION IN THE VERTICAL PLANE (U)

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ABSTRACT (U)

Studies of the structure of the vertical sound field for sound propagating in the deep ocean and for long ranges are briefly summarized. Sources were towed at several depths. Source powers of the order of 25 to 35 W in the cw mode and 5 W in the band-limited noise mode were used. Results include the sound field as seen by a 32-element linear array suspended vertically at 2000 ft and used with a cw source, and as seen by one or two elements at depths between 500 and 3000 ft used with a correlator and a band-limited noise source. A limited comparison of the performance of the array as compared to the correlator is given as well as a discussion of the limitations of the two systems.

ABSTRACT (C)

Studies of the structure of the vertical sound field for sound propagating in the deep ocean and for ranges up to 100 miles are briefly summarized. Sources were towed at several depths. Source powers of the order of 25 to 35 W in the cw mode and 5 W in the band-limited noise mode were used. Results include the sound field as seen by a 32-element linear array suspended vertically at 2000 ft and used with a cw source, and as seen by one or two elements at depths between 500 and 3000 ft used with a correlator and a band-limited noise source. Possible passive-ranging and depth-finding methods are discussed. A limited comparison of the performance of the array as compared to the correlator is given as well as a discussion of limitations of the two systems.

INTRODUCTION

In a homogeneous ocean with perfectly reflecting surfaces, simple trigonometric considerations indicate that the pattern of the multiple arrivals from a distant source to a deep receiver carries information on the range and the depth of the source. This suggests the possibility of a method of passive ranging and depth finding, plus the important classification information that the target is or is not at depth.

In a real ocean this simple model will be modified by refraction of the sound paths; the signals may be distorted by horizontal variations in the velocity structure; and signals may be weakened, lost, or distorted by reflections from either surface.

In 1958 Hudson Laboratories started a series of studies of propagation in the vertical plane in the deep ocean to determine the limitations and the general feasibility of utilizing the vertical sound field structure for passive detection, ranging, and depth finding.

PRELIMINARY VERTICAL ARRAY EXPERIMENTS

In September 1958, Berman and Sherry[1] conducted a study of arrivals in the vertical plane in 2500 fathoms of water using a 12-element vertical array suspended at a depth of 3000 ft. Element spacing was 25 ft. A 130-cps cw source, depth 40 ft, acoustic power 35 W, was towed to a range of 40 miles and later to 300 miles. The essential result was that we could match theory and experiment for the major features of the propagation pattern as well as discriminate the various arrivals in the vertical. Figure 1 shows the basic

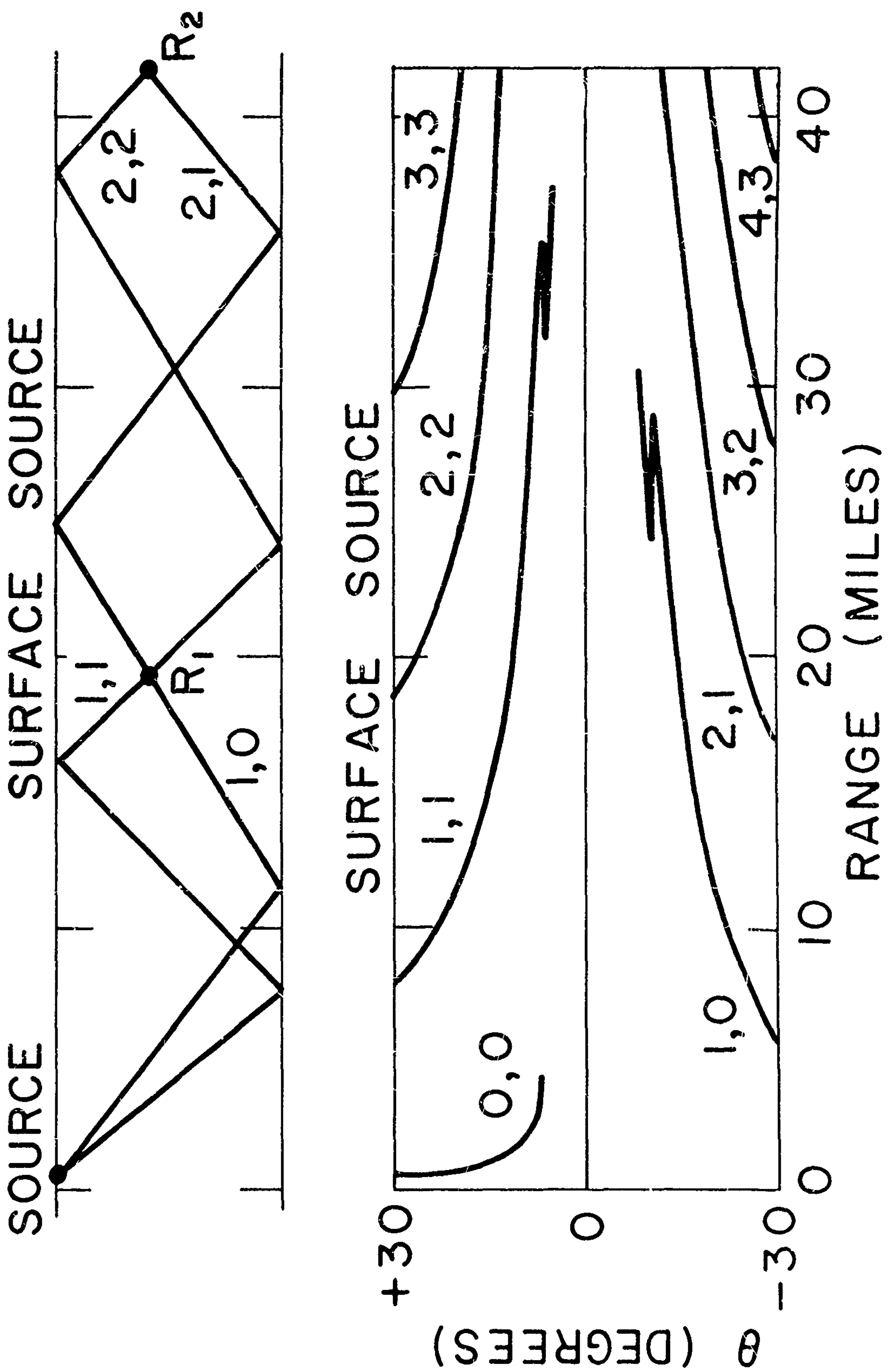

Fig. 1 Angle of arrival versus range plots - surface source.

pattern of arrivals presented as a plot of angle of arrival against range. The useful feature of this pattern is that the patterns of angles at any range are unique; thus it offers the possibility of passive ranging.

In June 1959, the experiment was repeated with the same equipment except that the source was towed at a depth of 1850 ft.[2] Figure 2 shows the pattern of arrivals in this deep source – deep receiver situation. The patterns of Figs. 1 and 2 are closely similar except that each curve in Fig. 1 becomes a doublet in Fig. 2. If Fig. 1 is overlaid on Fig. 2 the curves of Fig. 1 lie midway between the doublets of Fig. 2. The angular separation of these doublets is a direct measure of the depth of the source. Thus the pattern of vertical arrivals could in theory be used to determine target depth, a major piece of classification information.

In both experiments we were able to get agreement between theory and experiment on major features of the propagation pattern such as discrimination of arrivals, intensity of arrivals, and interference patterns of up to three arrivals, the latter to a range of 100 miles. However, we were unable to discriminate the doublets referred to above and shown in Fig. 2. The problem reduces to a question of the ability to discriminate arrivals. This might be accomplished by looking at them in space as with a vertical array, or by looking at them in time, since all arrivals are well separated in time. Further, interference patterns can theoretically yield information on range rate by discriminating the arrivals in phase. Several experiments in this direction were conducted in 1959, 1960, and 1961 by Frosch, Berman, Sherry, Stone and others.[3-5] Nothing further has been done along these lines.

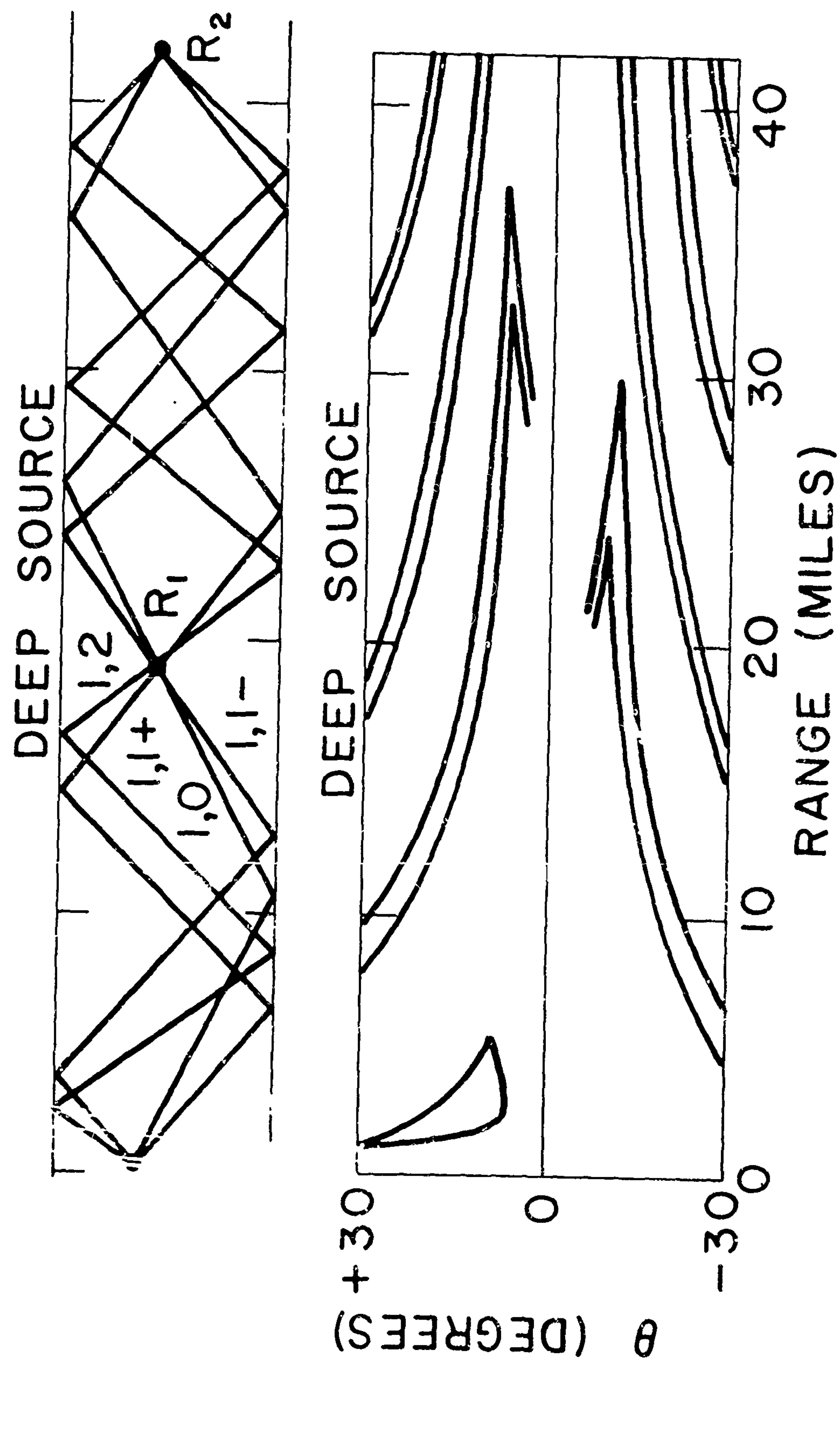

Fig. 2 Angle of arrival versus range plots - deep source.

TWO-ELEMENT ARRAY CORRELATION EXPERIMENTS

The next step in the development was an experiment by Clay and Sherry in which a Bell Laboratories CODAR correlator was used to correlate the signals received at a pair of hydrophones spaced 500 ft apart and suspended at depth.[6] This preliminary experiment was extended on several subsequent experiments near Bermuda and in the Hatteras Abyssal Plain.[7-9] The results can be summarized as follows:

1. Signals traveling over essentially the same path to a pair of hydrophones can be correlated to measure the angle of arrival of the signals and thus determine range passively. See the cross-correlation records in Figs. 3 through 8, the upper strip. These show results at several locations and at several frequencies.

2. The correlation of the signals is strongly dependent on the character of the bottom. The technique can be used to make a quick survey of the bottom reflectivity of an area.[10] Reflections from rough bottoms often correlate, giving detection information, but angles of arrival cannot be measured because of lack of knowledge of bottom slopes (Fig. 4).

3. Correlation depends on surface roughness and frequency. One run was made with a very long swell approximately 35 - 40 ft from crest to crest and running in the direction of the tow. Signals at 100 cps reflected from the surface were observed to correlate well, while signals at 400 cps did not.

4. Signals traveling over widely divergent paths, such as the 1, 0 (one bottom bounce, no surface bounce) and the 1, 1 (one bottom bounce,

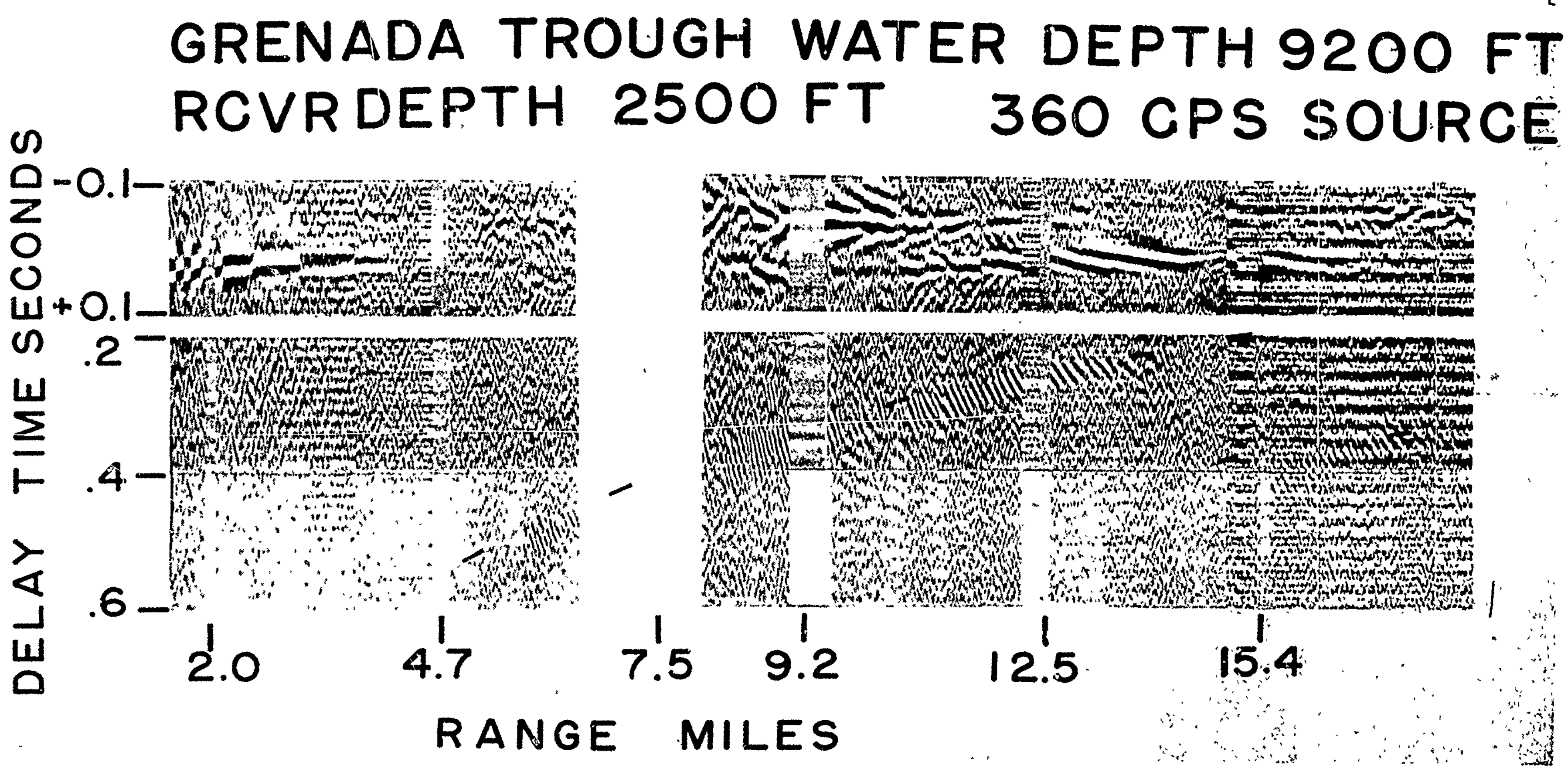

Fig. 3 Correlator records.

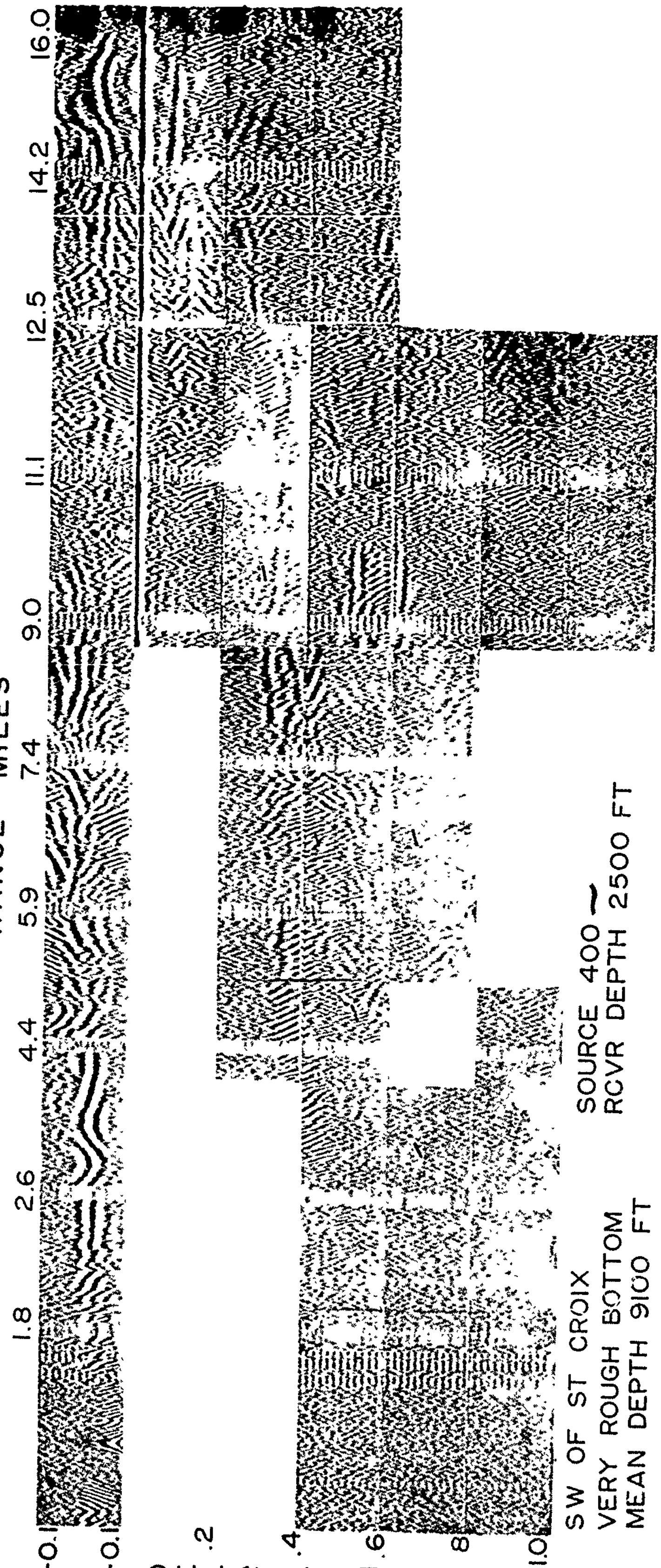

Fig. 4 Correlator records.

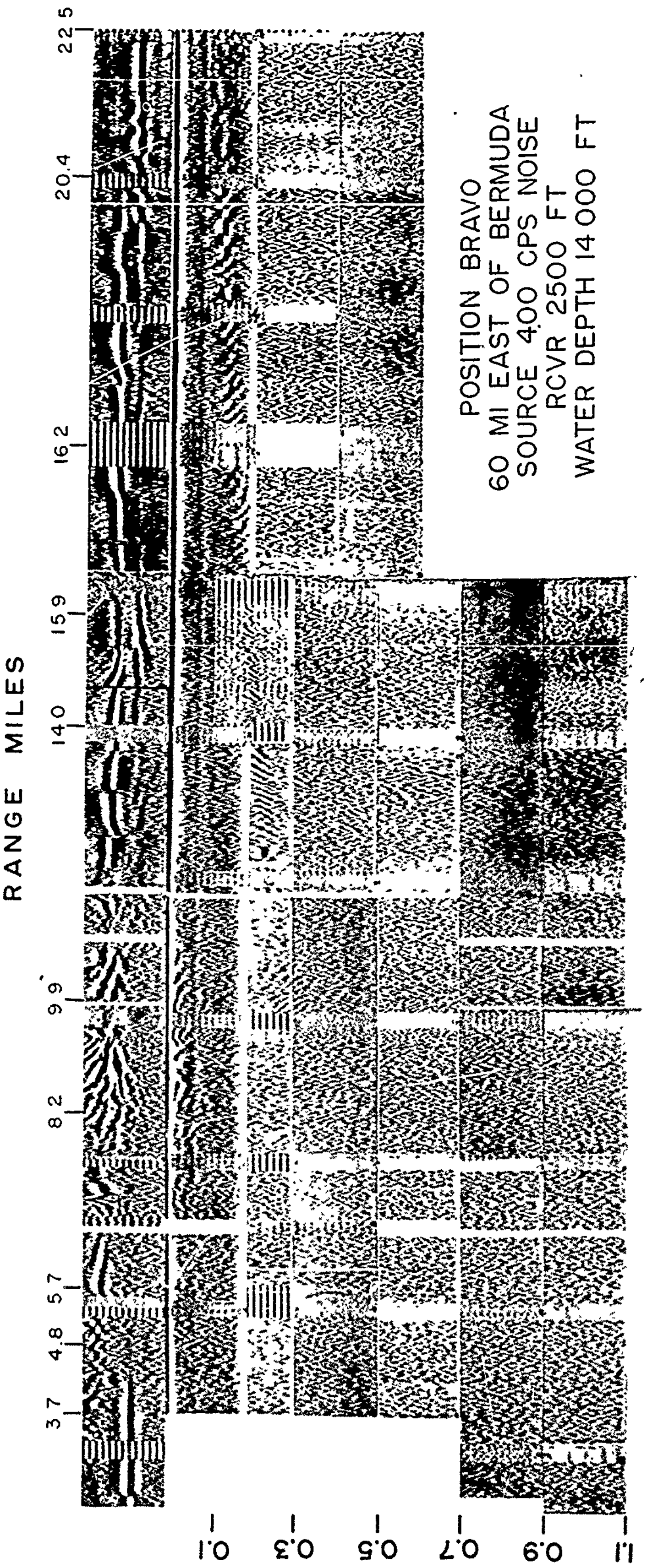

Fig. 5 Correlator records.

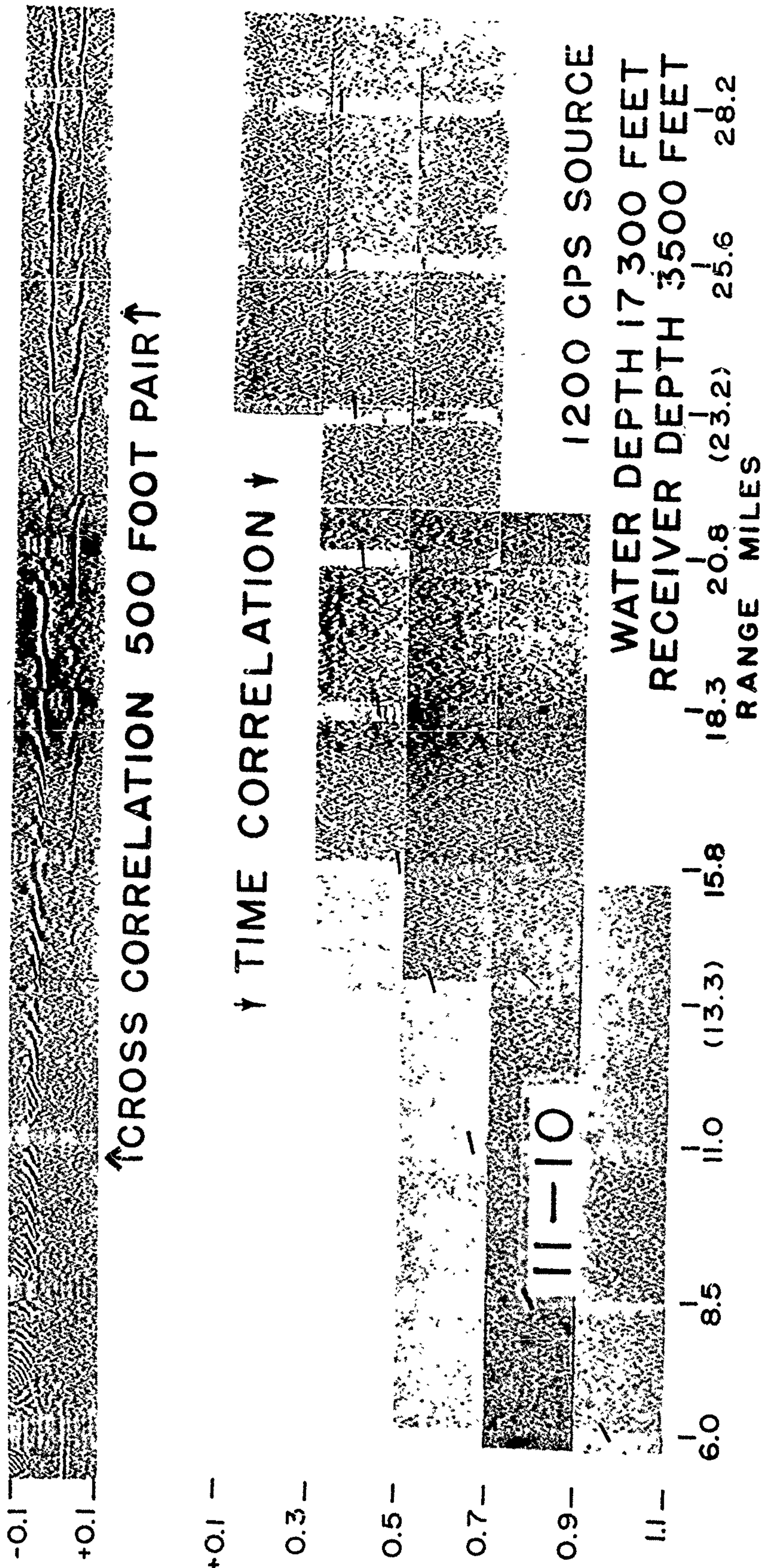

Fig. 6 Correlator records.

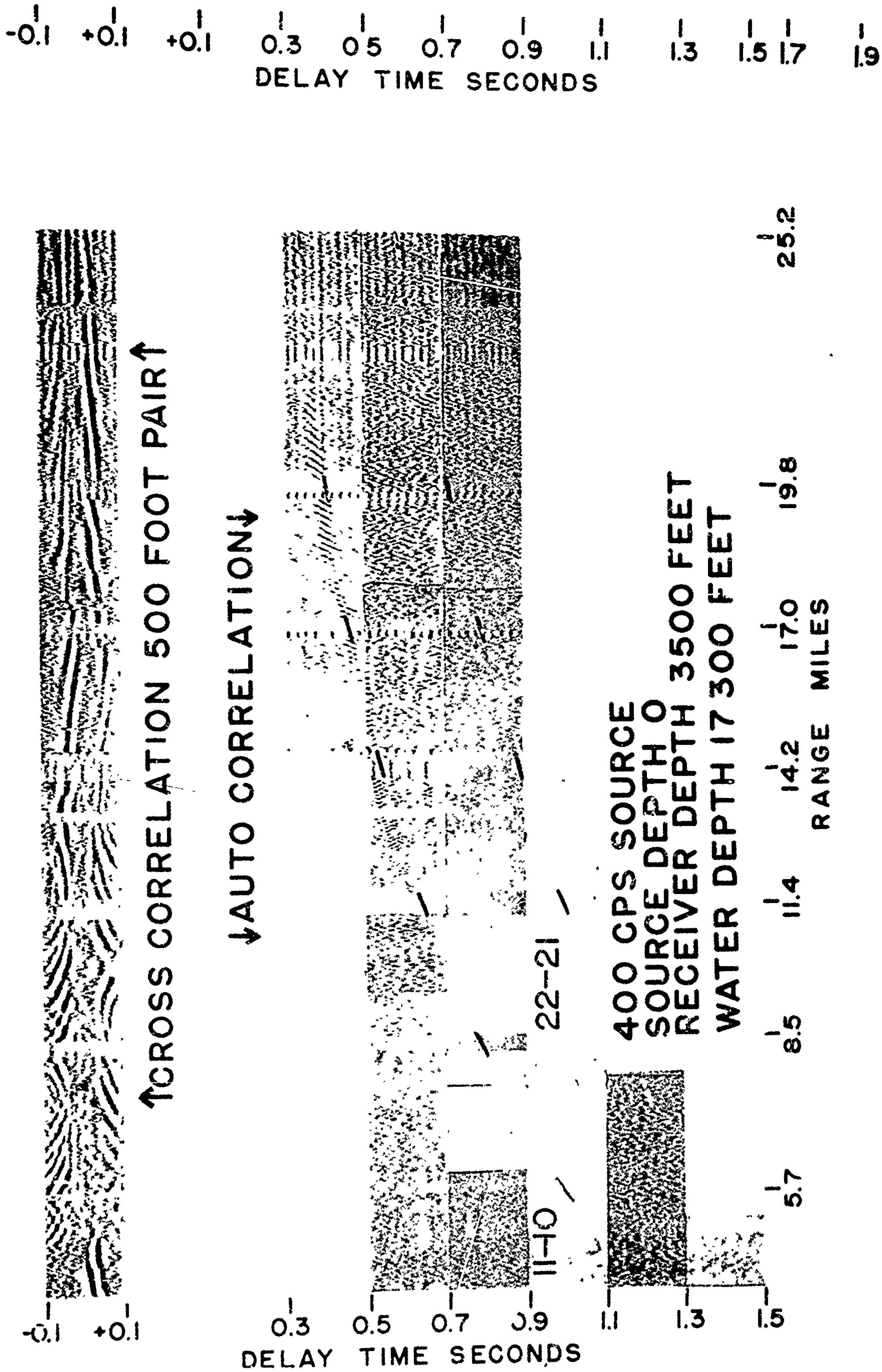

Fig. 7 Correlator records.

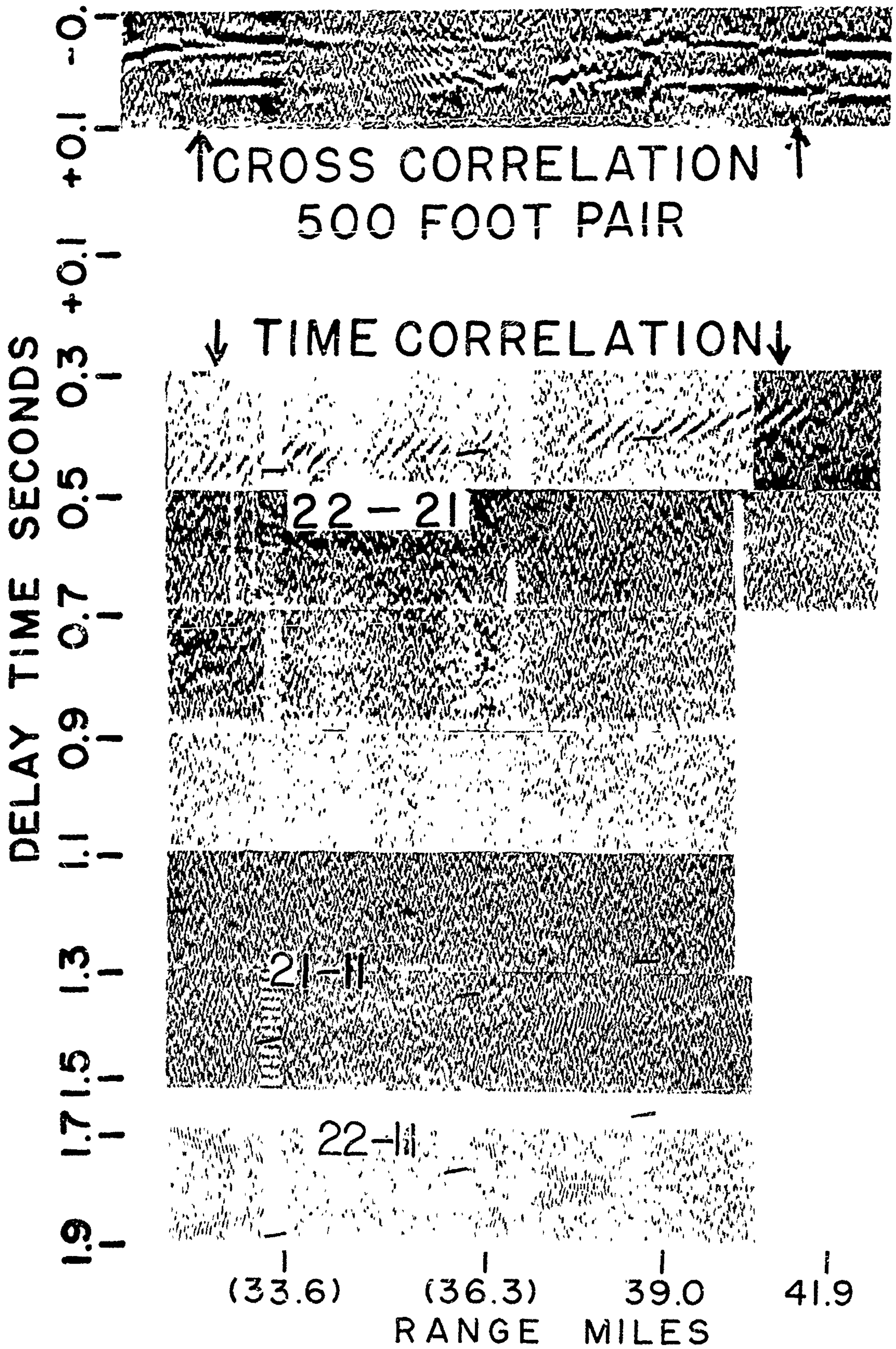

Fig. 8 Correlator records.

one surface bounce) will correlate well. When these are received at one hydrophone and autocorrelated, the correlation (time correlation) yields time difference of arrival (see the autocorrelation traces of Figs. 3-8). We have correlated one bottom bounce with two bottom bounce signals (Fig. 8), and one bottom bounce with a surface sound channel direct arrival (Fig. 9).

5. The time difference of arrival pattern of all the multiple arrivals can be used to determine both depth and range. Figure 10 shows the variation of the pattern of time differences of arrival as a function of source and receiver depth at constant range. The four arrivals here are the set that has made one bottom reflection and 0, 1, or 2 surface reflections. The autocorrelation yields six time differences, the combination of four things taken two at a time. Figure 11 shows data superimposed on theoretical time difference of arrival curves for a range run with the source towed at 250 ft; Fig. 12 is for a range run with the source at 650 ft. The agreement is quite good, substantiating the claim that range and depth can be determined by this method.

Computations of range and depth from time difference of arrival measurements with a source at about 15 miles and 1000 ft yielded maximum errors of 15% in depth and 2% in range.[7]

The data shown in Fig. 11 were taken with a receiver at 1000 ft while the data in Fig. 12 were taken from a receiver at 2500 ft. The agreement is considerably better in Fig. 12, indicating that sonobuoys at very deep depth may be advantageous. In the case of this data a secondary sound channel extending to 1800 ft existed and may be the cause of reduced accuracy in Fig. 11.[9]

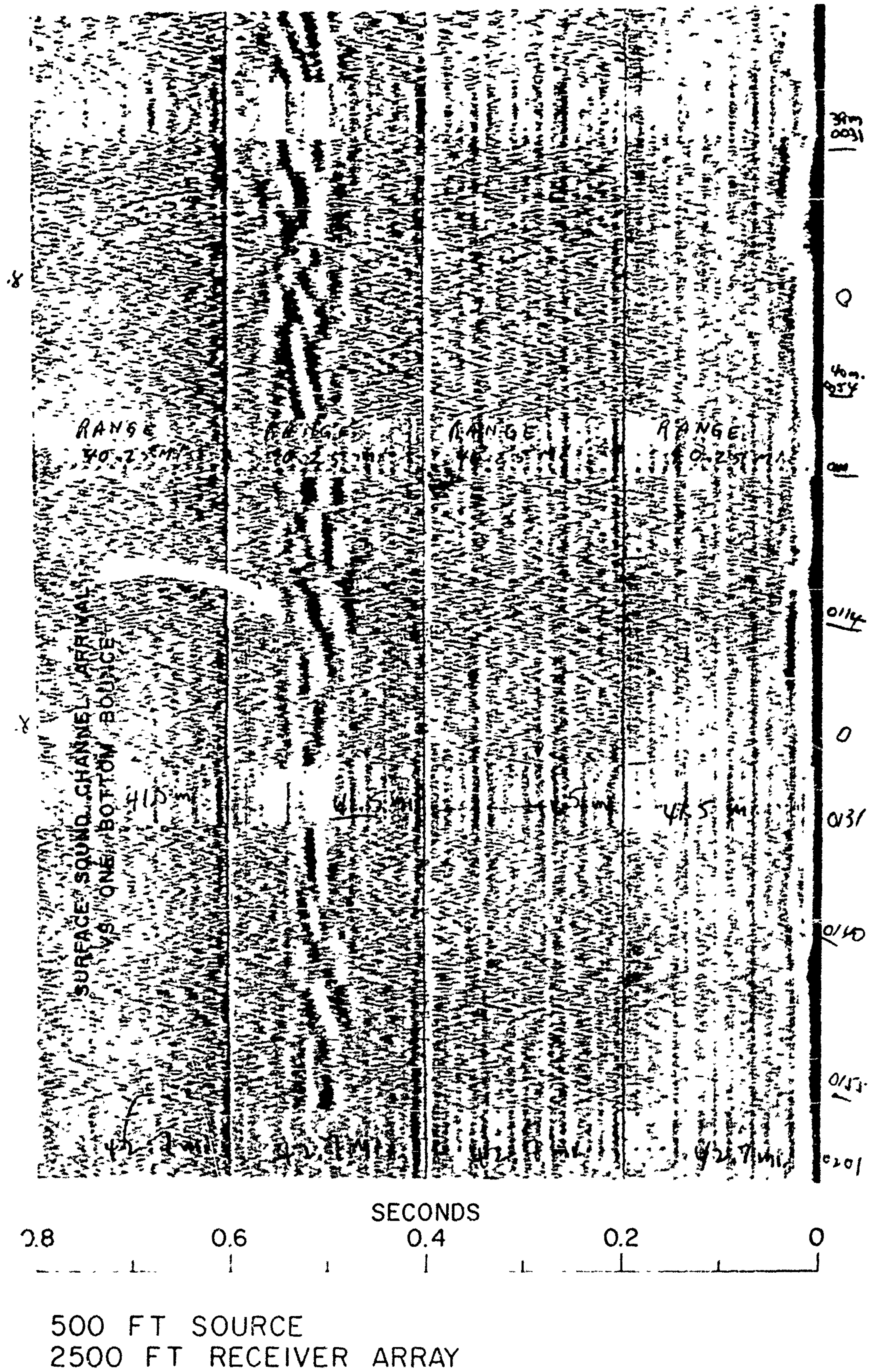

Fig. 9 Time correlation as a function of source depth.

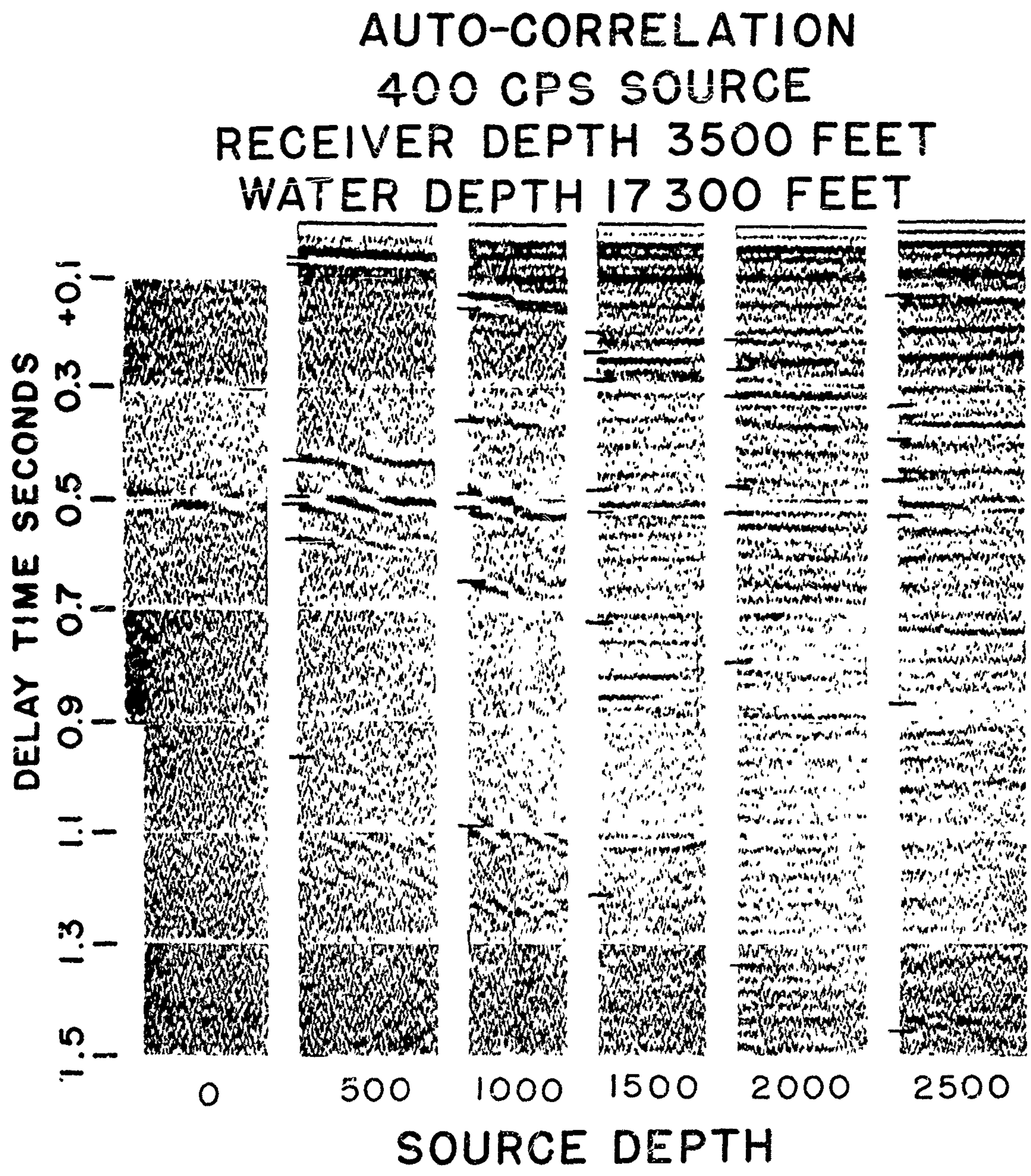

Fig. 10 Time correlation of a signal transmitted through a secondary sound channel with a signal reflected from the bottom.

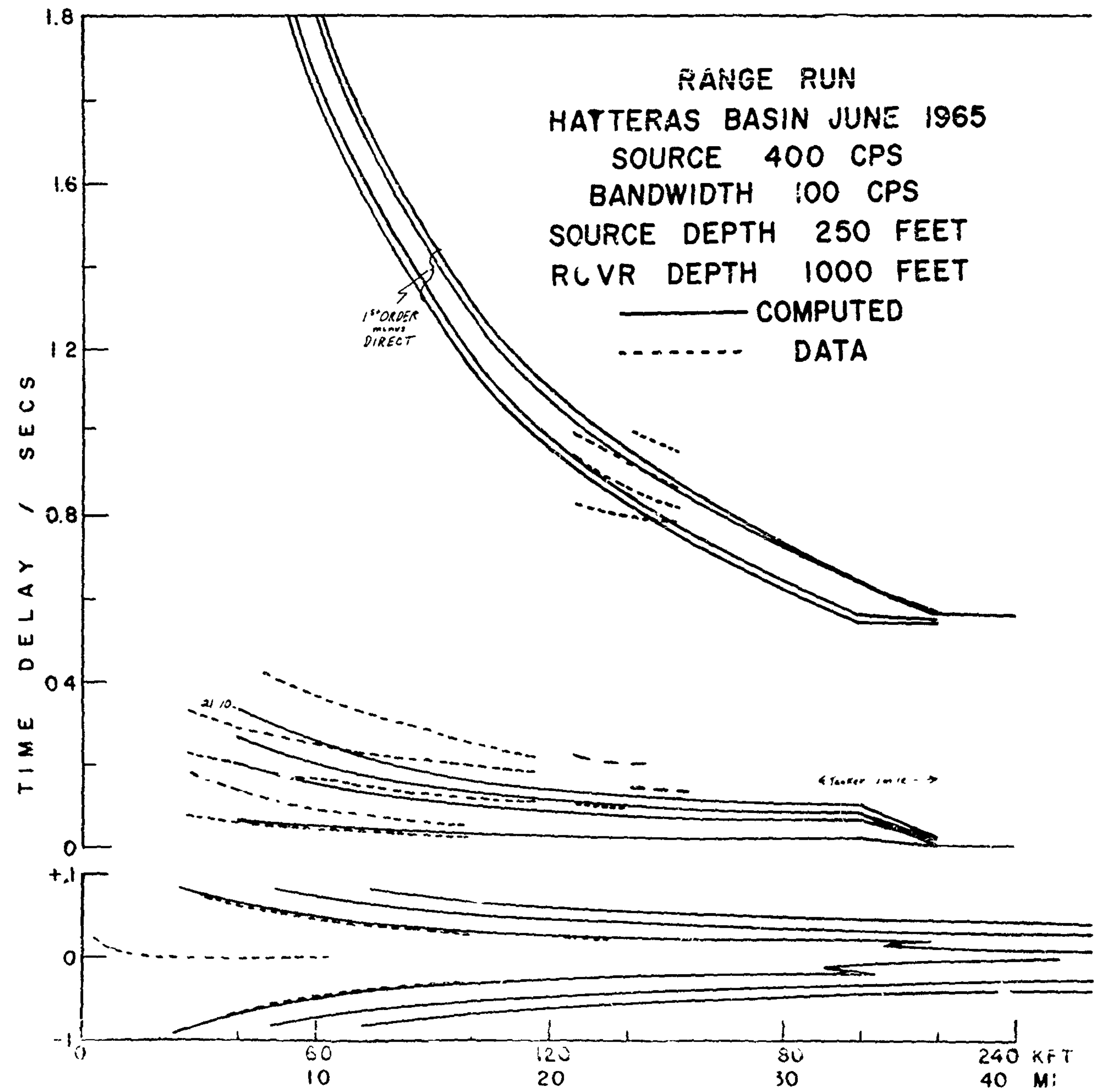

Fig. 11 Sine of angle of arrival (lower) and time-difference plots as a function of range.

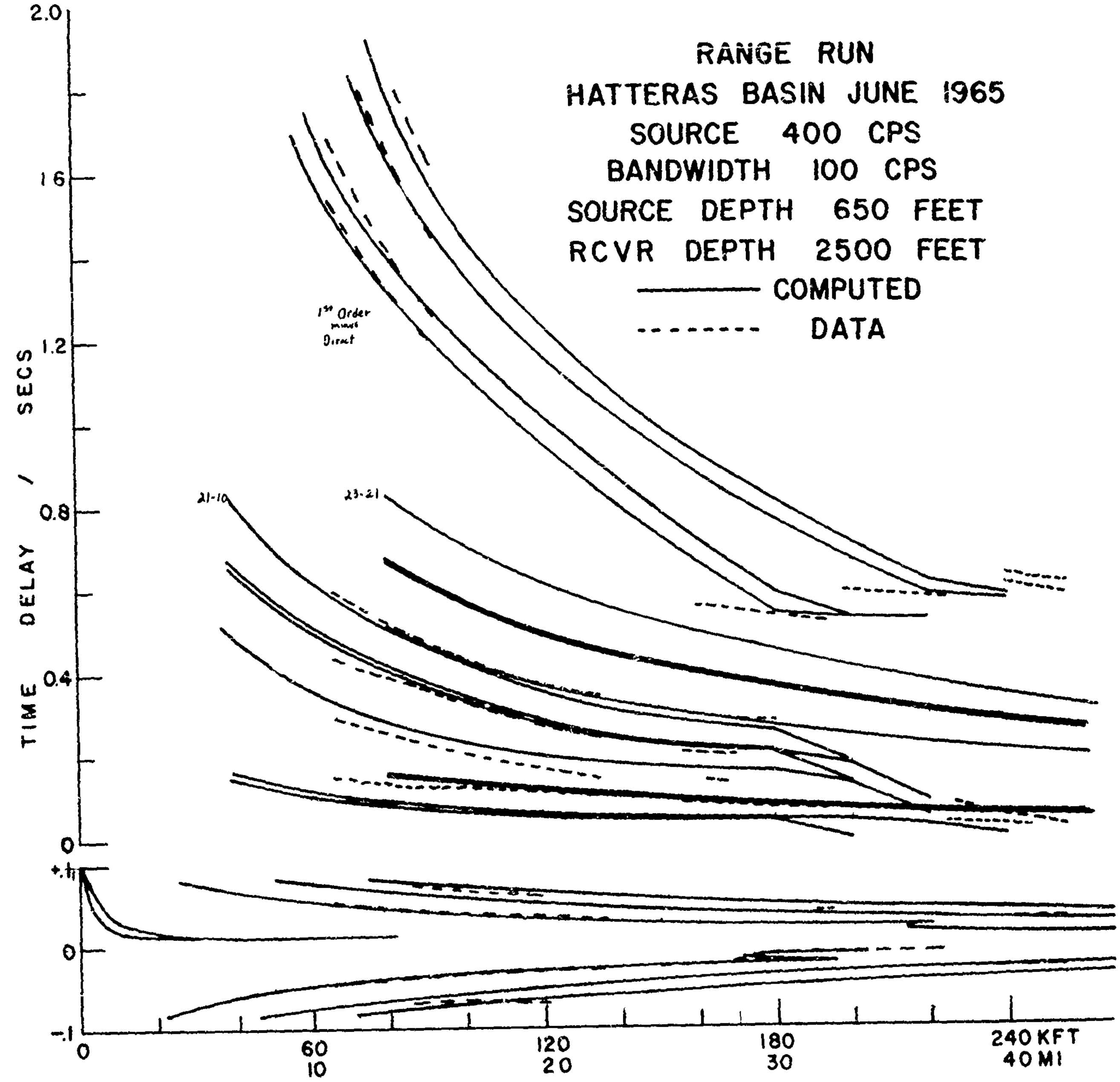

Fig. 12 Sine of angle of arrival (lower) and time-difference plots as a function of range.

Power levels of sources used in these experiments were of the order of 3 to 5 W.

PROJECT VERSUS

About 1960 a contract was let to Westinghouse Corporation for the design and construction of a vertical array system (Project VERSUS). Hudson Laboratories was to act as consultants. The system consisted of a 32-element vertical array with 25-ft spacing and cable permitting suspension to 2000 ft. A remotely operated winch was included and the array was to be designed with concentric elements permitting reeling the hydrophones onto the winch. The original conception was to install all of this on a submarine and design it for remote operation while submerged. A magnetic-tape beamformer and processing electronics were included. The project was plagued with mechanical difficulties, particularly hydrophone and cable leakage, and was eventually taken over by Hudson Laboratories.

Some data were obtained with the array by using it from the USNS Gibbs while at anchor, but in general the system has proved impractical for use on an anchored surface ship except in very calm weather because of the high impulse noise induced by the rolling of the ship. Figures 13 and 14 show a portion of a three-dimensional model constructed from data taken from the array using a 400-cps cw source towed at 650 ft.[8] The long dimension is time or range, the cross dimension angle of arrival from plus to minus 30 degrees (plus 10 to minus 10 omitted in this model), and the height is the amplitude of the array response.

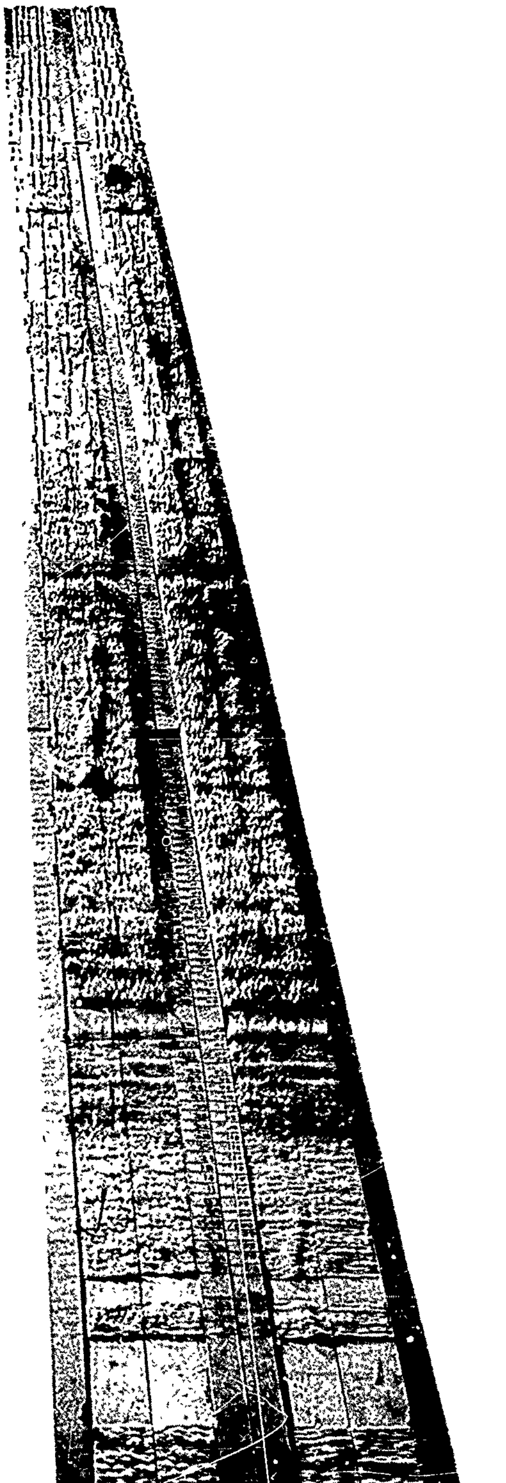

Fig. 13 Three-dimensional model of the output of the 32-element vertical array. Range varies from 3 miles at the bottom to 40 miles at the top. Source depth is 650 ft.

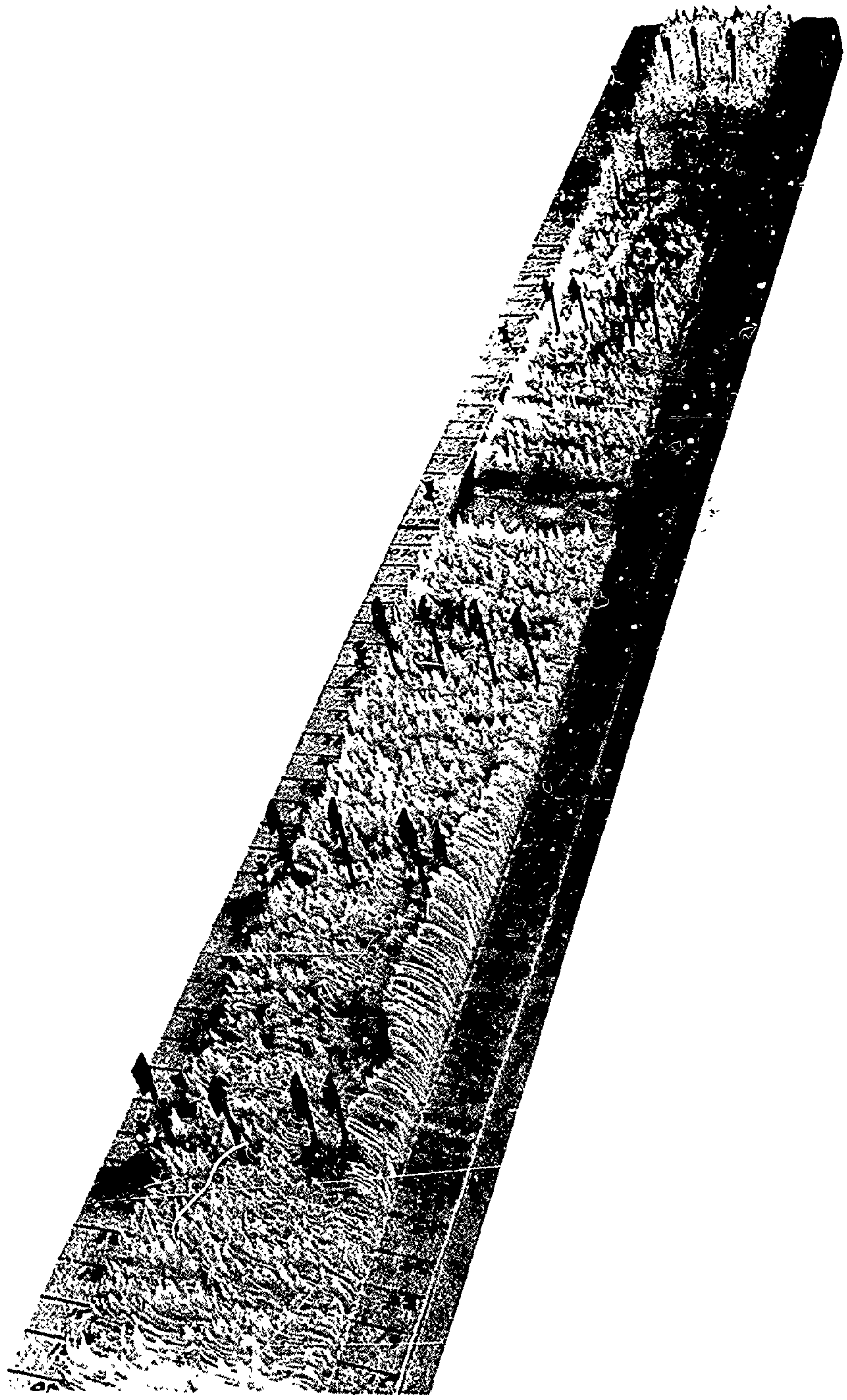

Fig. 14 Detail of same model, range 25 to 40 miles, showing strong signals from first convergence zone.

Using two of the elements of the array with the correlators, we were able to make a direct comparison of the performance of the correlators and the array on 100-mile range runs with a 400-cps source operating in the band-limited noise mode with a bandwidth of 100 cps. The results indicate approximately equal detection performance, but are only qualitative. We were unable to find a range at which one system detected the signal when the other did not. While the summed array suffered severely on this run from the impulse type of noise due to rolling of the ship, the correlator does not see the impulses. Undoubtedly they appear as a stochastic type of noise, degrading correlator performance; but they do not appear as impulses and thus do not interfere with the eye examination of the records. The correlator had the additional advantage of a continuous readout that presented an integrated trace to the eye.

CROSS CORRELATION OF SIGNALS FROM ARRAYS

In addition to the above, we started a study of the cross correlation of the outputs of two linear summed arrays as described by Jacobson.[11,12] Here two groups of nine elements from the array were delayed and summed and the summed outputs correlated. While additional problems arose from this initial experiment, comparison of data from the three types of processing on the same range run with a band-limited noise source indicates that the Jacobson system is qualitatively several dB better than either of the other systems. This improvement may be as much as the theoretical 10 log 9, or 9.5 dB.

DEEP SONOBUOY EXPERIMENTS

A prototype deep sonobuoy was constructed using standard navy sonobuoys from which the hydrophones were removed. These were installed on a styrofoam raft, which also carried batteries for preamplifier power. Two VERSUS-type hydrophones were suspended beneath the buoy at depths of 1000 and 1500 ft. A 50-lb weight was attached to the bottom of the hydrophone cable.[9] The sonobuoy hydrophones experienced less vertical motion than the ship-suspended hydrophones and were a greater distance from the noise of the ship. Thus qualitatively the noise from these two types of noise was reduced in the sonobuoy signal. The slight qualitative improvement in performance of the sonobuoy was offset by the lesser accuracy of range and depth prediction apparently related to the shallower depth of the sonobuoy hydrophones and the fact that they were in a secondary sound channel (Figs. 11 and 12).

DISCUSSION

Our investigation of summed linear arrays versus correlation processing is far from complete, but we have gained considerable experience. We have been using sources to provide signals whose frequency and bandwidth are dictated by engineering rather than experimental conditions.

Our results indicate no significant difference in detection range between the 32-element array and a two-element array with correlator processing when tracking a band-limited noise source operating at 400 cps with a bandwidth of 100 cps. However, the correlator cannot be used

effectively against a signal which consists largely of cw components, while the addtiive array is expected to be highly effective against a cw signal near its designed frequency. Thus we cannot fully evaluate this comparison until we have submarines or a submarine simulator as a target.

Present indications are that the proposed system of determining range and depth with correlator techniques will be effective only at short ranges: within the first convergence zone to about 40 miles, and, less reliably, within the second convergence zone to about 70 miles. We have never observed a third bottom reflection when using a band-limited noise source at about five acoustic watts output, comparable to the expected energy level in the broad-band spectrum of a submarine. RSR arrivals from greater ranges (100 miles) have been observed and could be expected from still greater ranges whenever the source crosses a convergence zone. However, at these longer ranges only one arrival is received and no time difference of arrival information can be obtained, nor does the measurement of the angle of arrival provide ranging information, except that the target is crossing a convergence zone; but which convergence zone the target is crossing cannot be directly determined from our receiver.

With cw sources with a power output of the order of 25 - 35 W and the additive array, we have observed third and occasionally fourth bottom reflections, indicating a somewhat better possibility of ranging on this type of signal. This improvement reflects the increased power of our sources when operated near resonance in the cw mode as well as the gain of the array with this type of signal.

Present theory[13, 14] indicates that with source powers of interest (less than 100 W), as range increases, bottom reflections will be lost and later surface-reflected (RSR) arrivals will be lost, leaving all the available energy in nonreflected (RRR) paths. Further, the energy in RRR paths no longer has the character of an "arrival" but is evenly distributed over a wide cone of vertical angles (approximately plus or minus 12 to 15 degrees from the horizontal). It is known[15] that most of the low-frequency noise energy is also concentrated in this same cone of vertical angles. Thus there is no signal-to-noise advantage in using a vertical array at the low frequencies to receive very long-range signals, and the array will be unable to determine a vertical angle of arrival.

Nevertheless, full understanding of long-range cw propagation requires some knowledge of vertical distributions that can only be obtained in full with a vertical additive array. Further, information as to vertical distributions should be obtained away from the boundaries and interfering slopes, a requirement which makes the use of bottom-anchored arrays cabled to shore very difficult and expensive. FLIP or SPAR would appear to be suitable vehicles for this investigation.

CONCLUSIONS

Although these studies are necessarily limited and do not fully cover the effects of temperature variations or bottom and surface reflection characteristics, the following tentative conclusions appear to be justified at this time.

1. In calm weather in the deep ocean over a smooth bottom (a condition which probably characterizes most of the oceans' abyssal plains) two-element deep sonobuoy arrays can provide passive ranging and depth information over at least the first convergence zone with accuracies of the order of 10% in range and 20% in depth. Correlation processing with existing CODAR would be satisfactory. The detection capabilities of this system will be at least as good as with narrow-band frequency analysis, which can also be a part of the system. For a significant but as yet undetermined portion of time the technique will provide this information within the second convergence zone up to about 70 miles.

2. Sonobuoys for this purpose will have to be larger and placed at greater depths than present operational sonobuoys. We recommend hydrophone depths of 2000 and 2500 ft, or within the main thermocline.

3. Surface reflections are a function of frequency, grazing angle, and sea state. As sea state increases, higher frequencies and arrivals at higher grazing angles are scattered. As surface-reflected arrivals deteriorate and are lost, only the direct and 1, 0 arrivals remain and the depth-finding feature, which requires two or more arrivals, will be lost. However, the 1, 0 arrival will continue to provide detection and ranging, with reduced accuracy. Where a surface sound channel exists, good ranging data are available by correlating it with the 1, 0 arrival, but depth information is lost unless a surface-reflected arrival is received. These paths will continue to carry coherent energy, which is useful up to the point where noise due to hydrophone motion and sea state combine to obliterate the signal.

4. Over most of the abyssal plains some areas of roughness and high refraction into the bottom will result in some intermittency of the data which, in our experience, does not destroy their usefulness. Over very rough bottoms the ranging feature may be lost but the detection and, with less accuracy, the depth-finding feature will be retained although data will probably be intermittent.

5. Multi-element additive arrays do not appear practical for use from surface ships. The ship must be anchored and, except in very calm weather, noise due to ship motion seriously deteriorates array performance. See Appendix for further information on ship-suspended arrays.

RECOMMENDATIONS

I. Deep Sonobuoys

1. The immediate development of deep (2500 ft) sonobuoy pairs with time-correlation and cross-correlation processing similar to that described in this report. These can be either air or ship borne.

2. Tactical development of range determinations, using the time-difference techniques described herein, from widely spaced deep sonobuoys, for use in the short range (first convergence zone) location problem.

II. Array Correlators

1. Prototype experimentation with array correlators, starting with two- to four-element fixed-beam arrays and proceeding towards eight- to ten-element arrays with swept beams synchronized with the correlator sweep.

III. Multi-Element Additive Vertical Arrays

1. Consideration should be given to using FLIP, SPAR or the Wood's Hole "Sea Spider" as stable platforms for the continuation of studies with multi-element linear additive arrays.

2. Continuation of studies of the vertical structure of the sound field with arrays that are removed from either boundary and located above, below, and in the main sound channel, and in locations that are (a) close to the continental rise and sea mounts, and (b) in the abyssal plains.

APPENDIX

An experiment to measure the gain of the 32-element array was conducted during 1965.[8] To get a stable geometry the source ship was tethered to the anchored Gibbs with 12,000 ft of line. The source depth was varied from the surface to 4000 ft. Pings from the source were received at each hydrophone and accurately timed and compared in the hope that wave-front curvature could be detected. Some of the results are shown in Figs. 15 - 19. Figure 15 shows time-difference plots relative to the top hydrophone over a half-hour period. It is apparent that the array is in motion and that this motion is great enough to obscure any wave-front curvature. There is evidence that the array is "snaking" as well as swinging like a pendulum. Figure 16 shows the amplitude of pings as a function of position along the array and as a function of source depth. From these curves it is apparent that the variation in intensity is purely due to a dipole and this is confirmed by computation of the dipole. Figure 17 shows plots of attempts to measure array gain by coherent addition of signals at all the hydrophones, assuming equal amplitudes. While the technique is somewhat questionable, it indicates variations in array gain ranging from about 11 dB to nearly perfect 15 dB.

Figure 18 shows photographs of the arrivals at adjacent hydrophones. In this scale a coherent wave front is indicated and the angle of arrival changing with source depth is also apparent. Figure 19 shows a plot of data points from a range run with a 250 source (cw). Data points have been read from the beamformer output and plotted over theoretical angle of arrival curves.

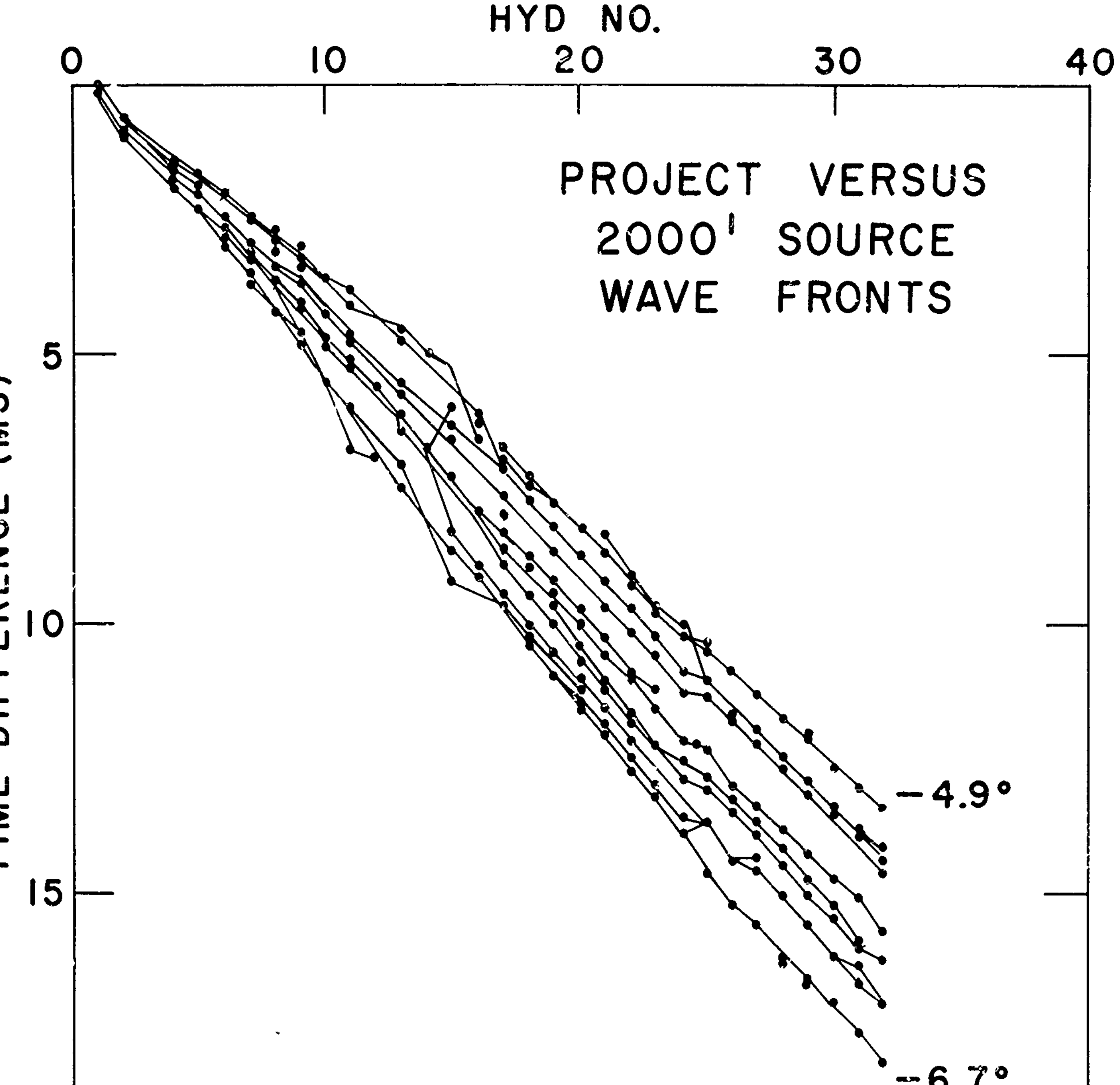

Fig. 15 Variation in wave fronts over a period of 1/2 hour as received by the 32-element vertical array.

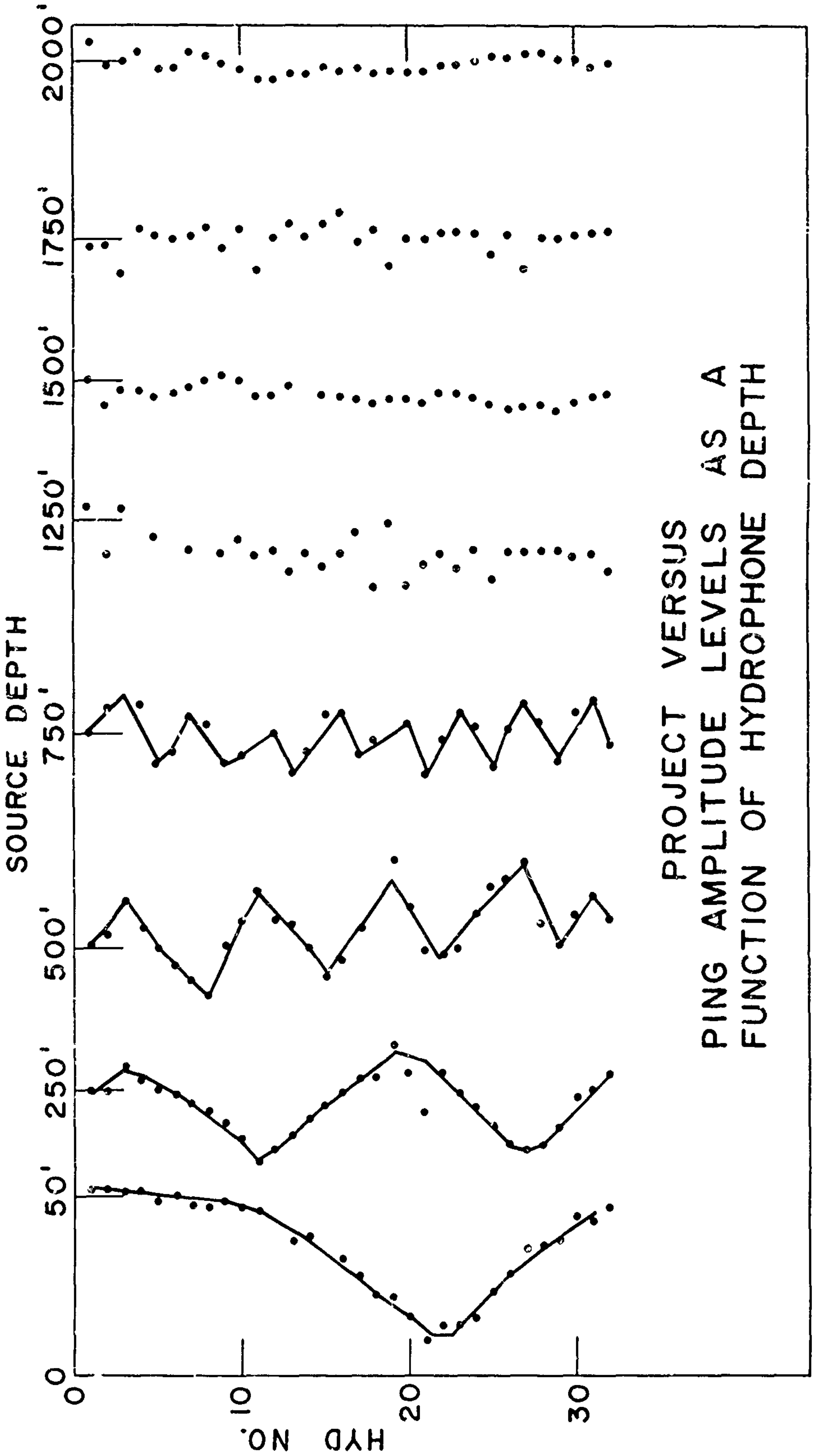

Fig. 16 Amplitude of signals received on individual hydrophones of the 32-element array as a function of position of the hydrophone in the array and the depth of the source.

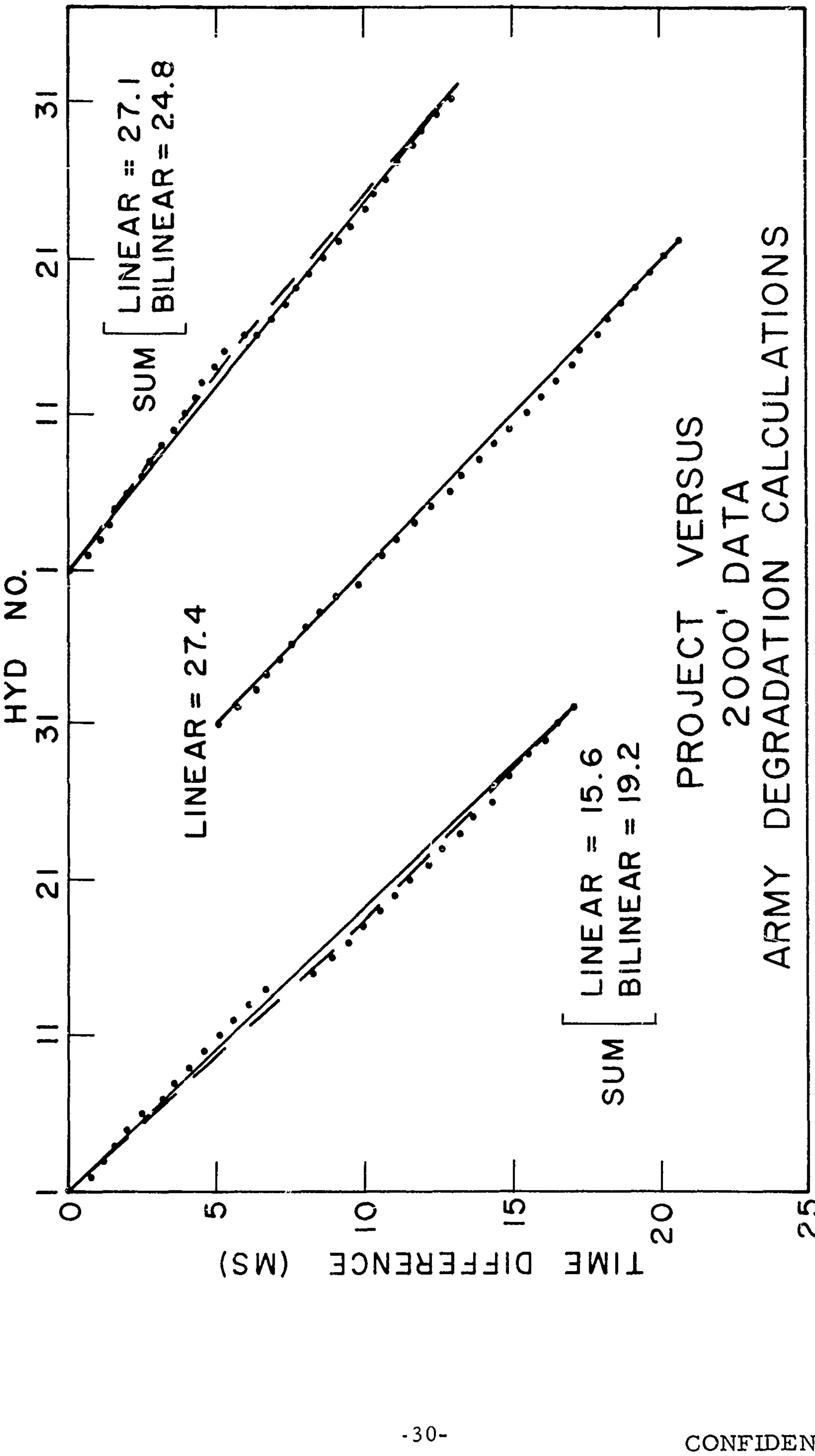

Fig. 17 Time variation of pings received at individual hydrophones for three samples. Time differences relative to the top hydrophone are compared to a straight line. Deviations from the line are reduced to phase difference and the coherent sum of all hydrophones compared to the theoretical sum of 32.

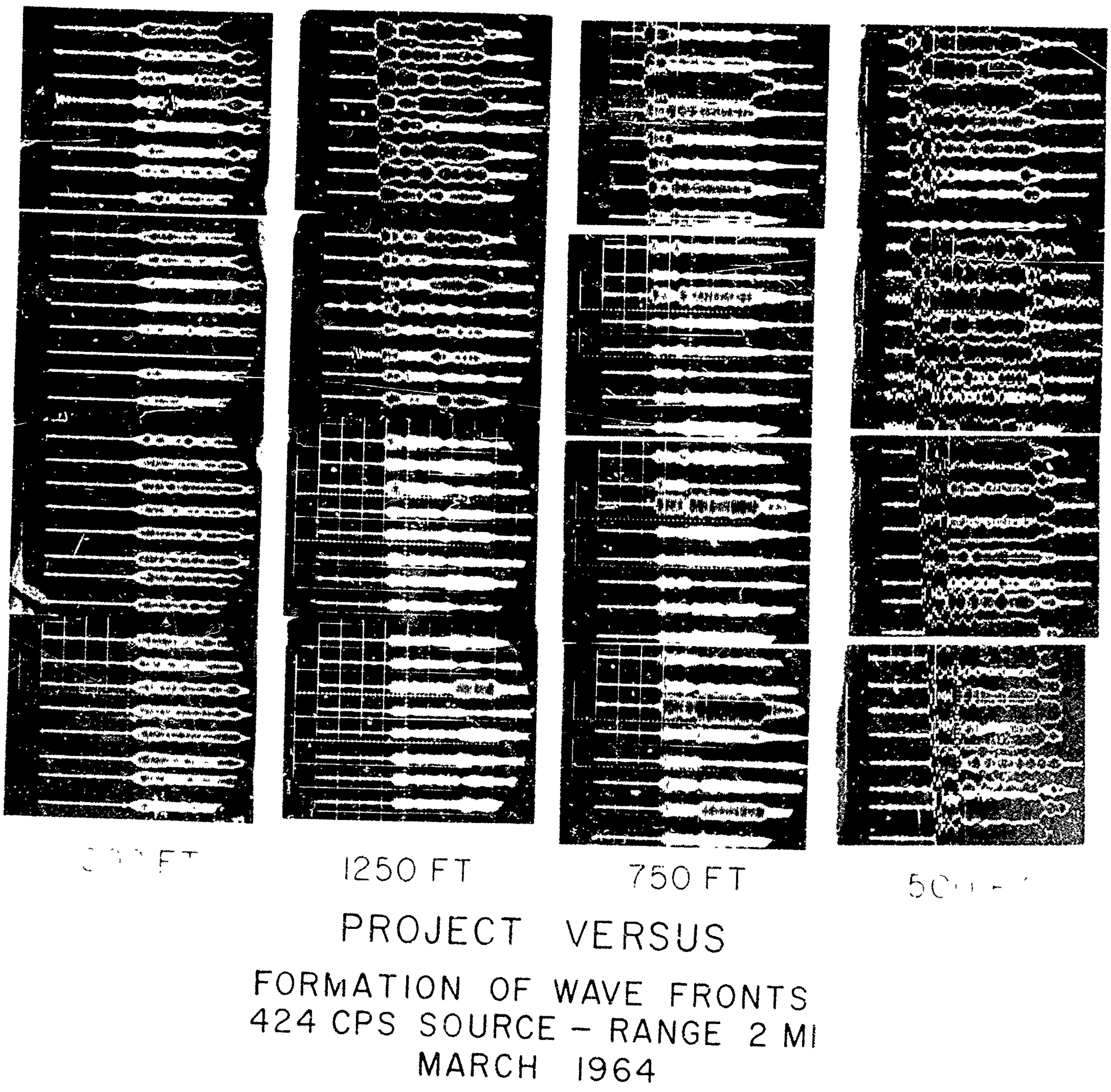

Fig. 18 Oscilloscope photographs of pings received by the array for four source depths.

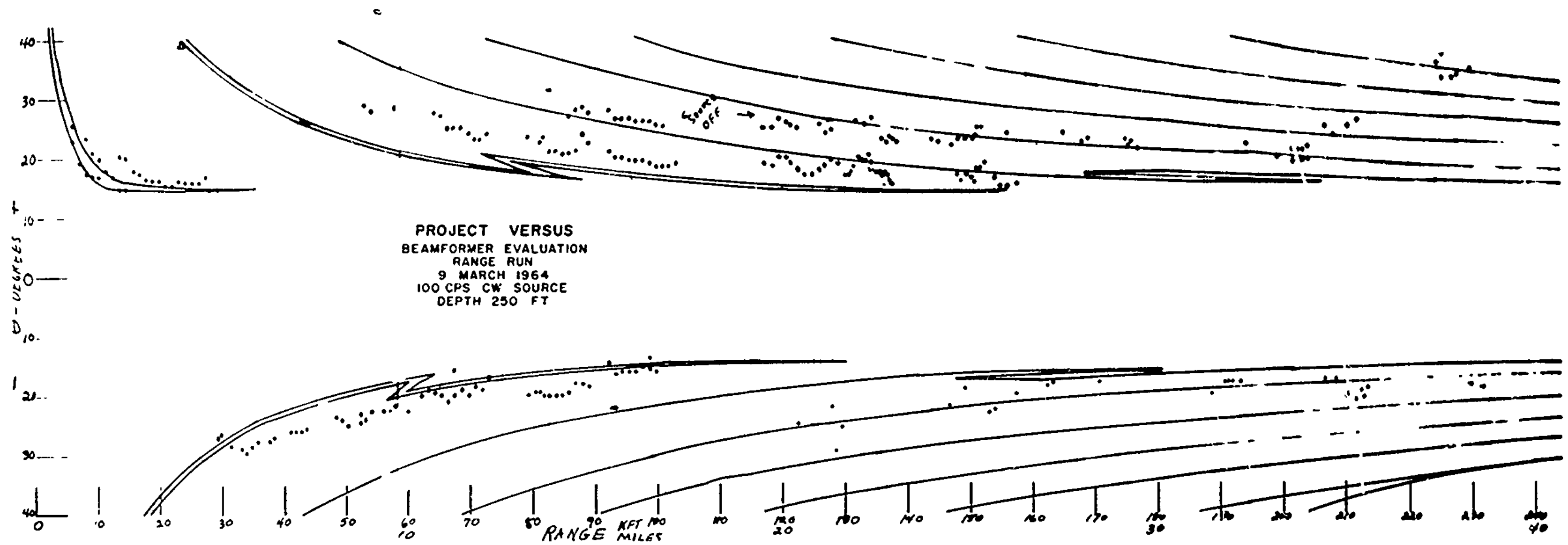

Fig. 19 Comparison of theoretical angle of arrival curves with data read from output of the 32-element array.

Agreement is quite good to a range of about 30 miles, then breaks down. A slight tilt to the array is indicated by the displacement of the data points from the theoretical curves. The doublet structure due to source depth is not resolved, although the pairs of arrivals are. We can clearly identify the (1, 0), (1, 1) and (2, 2) arrivals.

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13. ABSTRACT

Studies of the structure of the vertical sound field for sound propagating in the deep ocean and for long ranges are briefly summarized. Sources were towed at several depths. Source powers of the order of 25 to 35 W in the cw mode and 5 W in the band-limited noise mode were used. Results include the sound field as seen by a 32-element linear array suspended vertically at 2000 ft and used with a cw source, and as seen by one or two elements at depths between 500 and 3000 ft used with a correlator and a band-limited noise source. A limited comparison of the performance of the array as compared to the correlator is given as well as a discussion of limitations of the two systems.

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